Low-Temperature Direct Dark Matter Searches

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Abstract Small cryogenic detectors with efficient background rejection now best longer established and heavier direct dark matter searches. This paper reviews the experiments, results and prospects.

0.1 Introduction

Much evidence suggests a significant amount of non-baryonic dark matter in the Universe, in the guise of putative Weakly Interacting Massive Particles (WIMPs), such as the supersymmetric neutralino. There are indications such particles may be present in the Milky Way — hence the motivation to detect them directly, rather than products of their annihilation elsewhere. These various issues are discussed in Ref. [1].

Cryogenics, in fact, played a part in starting the direct dark matter searches. Low temperature super-conducting grains were suggested as neutrino detectors in the early 1980s [2]. It was then pointed out that such devices should also work to detect recoils caused by the elastic scattering of WIMPs [3]. Unfortunately, super-conducting grains turned out to have several practical problems. Indeed the first results from direct searches were obtained by detectors using earlier technologies, first ionization in semi-conductors [4], then scintillation detectors [5]. Cryogenic detectors, in the guise of calorimeters, have only recently begun to prove their worth for dark matter searches.

Generally speaking, direct dark matter searches are challenging because the expected exponentially decaying recoil energy spectrum yields rather small recoil energies (of the order of keV), and few events above threshold, at most a few per day and per kilogram of detector (Fig. 1). At first glance therefore, detectors for WIMPs require a high mass, a low background and a low threshold. An additional criterion is to have various target nuclei available to enable cross-checks and to study the two possible types of interaction, spin-dependent and spin-independent (cross section $\propto A^2$). The first generation

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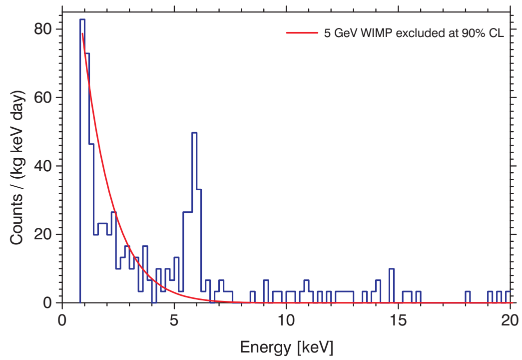

Figure 1: Expected 5 GeV/c^2 WIMP spectrum on sapphire (curve), and example of experimental background observed in the CRESST experiment [7]. WIMP spectra are expected to have a quasi-exponential shape, of steepness decreasing with WIMP mass.

of standard calorimeters excels at the last three of these requirements (Sec. 0.2); hybrid calorimeters circumvent the first requirement (Sec. 0.3).

0.2 Standard calorimeters

0.2.1 Thermal phonon detectors

The original super-conducting grains are still being pursued by the ORPHEUS experiment [6]. However, the cryogenic detectors most commonly used now in dark matter searches are calorimeters (also referred to as bolometers in this field). They are comprised of a main crystal (the absorber), in which an incoming particle scatters elastically off a nucleus, thereby releasing phonons which heat the absorber up (Fig. 2). The variation in temperature is read by a thermometer. Because the temperature rises are inversely proportional to the heat capacities involved, and because specific heats of dielectrics decrease with temperature, cryogenic conditions close to 10 mK are required to obtain decent signal-to-noise ratios. Most thermometers are pieces of neutron-transmutation doped germanium (NTDs) with a gradual change in resistance over a broad temperature range.

Experiments using this type of detector are listed in the first parts of Tables 1 and 2. The Milano experiment is primarily a search for $\beta\beta$ decays, as were most of the early direct dark matter searches [4]. This explains why the threshold of the experiment has not yet been optimized. Up to twenty 340 g detectors have been run successfully at a time; the fairly low background and the presence of tellurium give this experiment the best spin-independent limits of this first class of detector.

The Franco-Spanish *Rare Object Search Employing Bolometers UndergrounD* (ROSEBUD) experiment has deployed various small detectors made of sapphire and other materials. These detectors show excellent thresholds, but suffer from an unfortunately high background perhaps linked to the cryogenic equipment. The Tokyo experiment has tested up to 8 LiF units of 21 g each. Despite a high background due to the cosmic rays in the shallow site and to microphonics, the experiment has good spin-dependent limits thanks

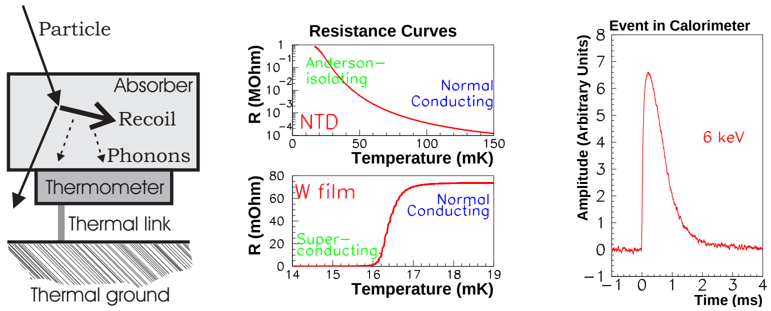

Figure 2: Left: principle of low temperature calorimetry. Center: examples of thermometers for calorimeters (NTD data courtesy A. Juillard, CSNSM Orsay; other data MPI Munich). Note different R and T ranges. Right: 6 keV event in a calorimeter.

to the presence of fluoride. Improvements are expected as the experiment moves to the deep Kamioka mine (2700 mwe).

Experimental spectra are then compared with expected WIMP spectra (Fig. 1) to set constraints on WIMP cross-sections and masses (Fig. 3). Published limits are taken here at face value. Though there is convergence towards a standard set of astrophysical assumptions to make these comparisons (most importantly a local WIMP density of 0.3 GeV.cm^{-3}), some uncertainties remain in the normalization of the spin-dependent limits [8], and in the statistical methods to use [7, 9].

Table 1: Current cryogenic direct detection experiments. Those in deep sites tend to have lower backgrounds. Grains, thermal and athermal phonon devices possess no active background discrimination. A wide variety of target nuclei are available, enabling studies of both spin-dependent and spin-independent couplings. Ionization-phonon experiments have background discrimination, and set best limits of any searches for spin-independent coupling.

Name	Depth (mwe)	Type	Absorber	Mass (g)	Ref.
ORPHEUS	70	Super-conducting grains	Sn	450	[6]
Milano $\beta\beta$	3500	Thermal phonon	TeO_2	20×340	[10]
ROSEBUD	2500	Thermal phonon	Al_2O_3, Ge	50	[11]
Tokyo	15	Thermal phonon	LiF	8×21	[12]
CRESST	3500	Athermal phonon	Al_2O_3	4×262	[7]
CDMS	20	Ionization and phonon	Ge, Si	4×165	[13]
EDELWEISS	4500	Ionization and phonon	Ge	320	[14]

0.2.2 Athermal phonon detectors

The thermal phonon signal used in the detectors described so far has the drawback of vanishing quickly as absorber mass is increased. As large absorber masses are of interest for direct detection, it is judicious to collect and read high frequency phonons in the

Table 2: Results from calorimetric experiments. Threshold and background are capital. For ionization and phonon experiments (second group), background is after rejection of electron recoils but without any neutron background subtraction. Energies are in true keV.

Name	Threshold (keV)	Exposure (kg.d)	Approximate background
Milano $\beta\beta$	10	3.9	4 /d/kg/keV at threshold
ROSEBUD	0.5	0.4	15 /d/kg/keV over 25–50 keV
Tokyo	15	1.26	200 /d/kg/keV over 20–40 keV
CRESST	0.6	1.51	1 /d/kg/keV over 15–25 keV
CDMS	10	10.6	13 counts over 10–100 keV
EDELWEISS	30	4.53	0 counts over 30–200 keV

thermometer before they thermalize in the absorber [18]. This yields an amplification of the pulses which is much less sensitive to absorber mass. Thermometers used for this type of device are mainly thin films, for instance using the sharp transition between the super-conducting and normal-conducting states of tungsten (Fig. 2).

The Anglo-German-Italian *Cryogenic Rare Event Search with Super-conducting Thermometers* (CRESST) has developed and deployed such devices using sapphire absorbers. Up to four crystals of 262 g each have been run in the deep Gran Sasso site, in a sophisticated cryogenic setup designed to minimize radioactive contaminations [7]. These detectors show excellent thresholds (600 eV) and low background (Fig. 1). CRESST is competitive for light WIMPS, and now has the best calorimetric spin-dependent limits thanks to the aluminum in its detectors.

0.3 Hybrid calorimeters

Calorimeters can more than make up for their small masses by rejecting background through a second simultaneous measurement. This exploits the fact that WIMPs (as well as the neutron background) are expected to interact in the absorber by creating nuclear recoils, whereas the photon and electron backgrounds create electron recoils.

0.3.1 Phonon-ionization detectors

The most developed technique so far uses calorimeters made out of a semi-conductor. The recoil imparted by a scattered particle releases not only phonons but electron-hole pairs. If the surfaces of the absorber are implanted to make electrodes, a bias voltage can be applied to drift the created charges to the electrodes where they are counted, thereby producing a charge signal in addition to the phonon signal. Figure 4 shows that since electron recoils create electron-hole pairs much more efficiently than nuclear recoils do, this technique should allow rejection of nearly 99.9 % of the electron and photon background while retaining about 90 % of the nuclear recoils (from WIMPs and the neutron background) and maintaining a decent threshold. Teething problems with misidentified surface events which somewhat limited the discrimination capacities [19] now appear to have been contained thanks to various electrode implantation schemes

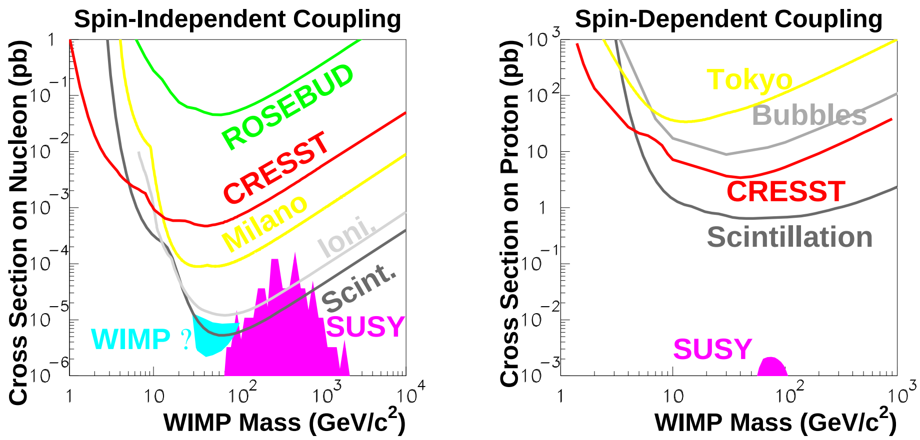

Figure 3: Limits from standard calorimeters (90 % CL), along with those from ionization [15], scintillation [16] and bubble detectors [17], approximate supersymmetric MSSM phase-space predictions (adapted from Ref. [23, 24]), and 3σ WIMP claim [20]. The wide choice of target nuclei allows the study of spin-independent as well as spin-dependent interactions (although in the latter case, calorimeters, like most other direct searches, are disadvantaged with regards to SUSY predictions by lack of coherent amplification factor $\sim A^2$ in cross-section). Standard calorimeters boast excellent thresholds enabling them to search for low mass WIMPs.

and position sensitive techniques. The American *Cryogenic Dark Matter Search* (CDMS) has deployed several silicon and germanium devices. In a 1999 run, CDMS obtained 13 nuclear recoils over 10.6 kg.d in three 165 g Ge devices with a 10 keV threshold [13]. This rate would be compatible with the WIMP claimed by the DAMA NaI scintillation experiment [20]. However, CDMS is in a shallow site exposed to the neutron background created by cosmic rays. Based on the number of multiple nuclear recoils observed, and on the number of nuclear recoils previously observed in their silicon detectors, CDMS reckons that most of the 13 events are in fact neutron background, and subtracts some of them. This improves the CDMS limit by a factor ≈ 2, and greatly reduces the compatibility with the DAMA result. More recently, the French *Expérience pour DEtecter Les WIMPs En Site Souterrain* (EDELWEISS) has operated a 320 g Ge device with a 30 keV threshold in a deep site [14]. The 4.53 kg.d of data show not a single nuclear recoil. The ensuing limit rules out the most likely value of the DAMA NaI-1–4 WIMP with a 90 % certainty. Thus hybrid ionization-phonon calorimeters now have the best spin-independent limits of all experiments (Fig. 5). Further results should be forthcoming as CDMS moves to a deep site and EDELWEISS accumulates more data.

0.3.2 Scintillation-phonon detectors

Their excellent results notwithstanding, ionization-phonon detectors are by essence restricted to semi-conducting nuclei, in practice Ge and Si. For a wider choice of targets, the CRESST and ROSEBUD experiments are developing a simultaneous measurement

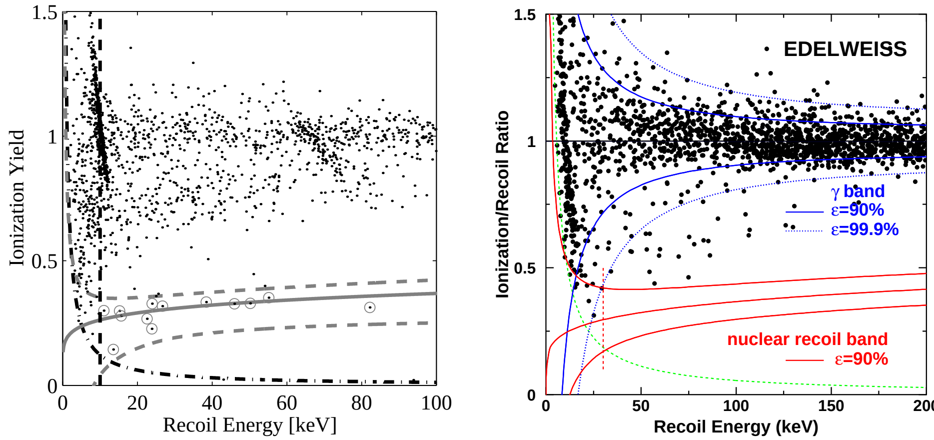

Figure 4: Backgrounds from the CDMS [13] (left) and EDELWEISS [14] (right) ionization-phonon experiments. For each event, ratio of ionization over recoil energy has been plotted as a function of recoil energy. Hyperbolae correspond to ionization threshold of hardware. Vertical segments are the recoil threshold used in analyses. Bands around a ratio of ≈ 0.3 are where 90 % of nuclear recoils are expected, based on neutron calibrations. Most of the background has a ratio of ≈ 1, corresponding to photon or electron background. Few or no events remain in nuclear recoil zone (13 events in 10.6 kg.d and 0 events in 4.53 kg.d respectively), demonstrating excellent background rejection.

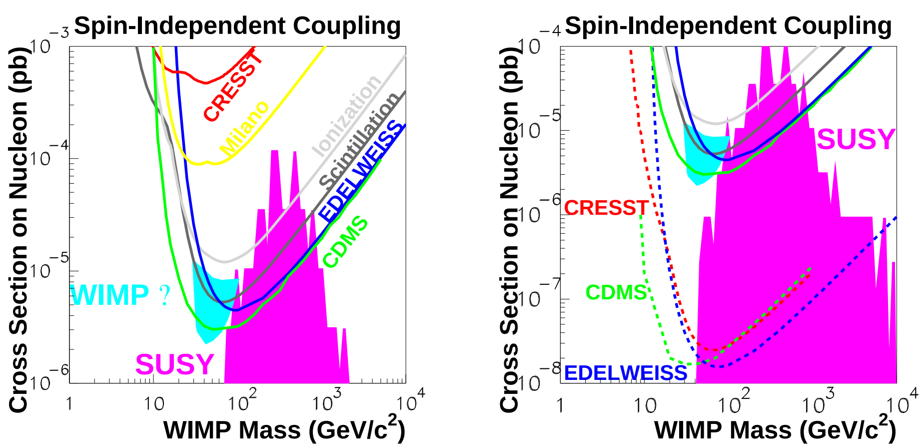

Figure 5: Left: spin-independent limits from ionization-phonon calorimeters [13, 14]. Thanks to excellent background discrimination, these detectors not only improve over their phonon-only counterparts, but surpass much heavier and more mature techniques. Paucity of spin in natural germanium makes for poor spin-dependent limits, not shown here. Right: spin-independent sensitivities expected from next-generation hybrid calorimetric experiments. Run times of ≈ 2 years and mastery of neutron background are typically assumed.

Table 3: Next-generation calorimetric direct detection experiments. All will be in deep sites. CUORICINO, primarily a $\beta\beta$ decay experiment, will have no background discrimination, unlike the other experiments. The two ionization-phonon ones, CDMS II and EDELWEISS II, should be complemented by the scintillation-phonon one, CRESST II, which will provide a broader choice of target nuclei. Partial results could start coming within the next two years. Experiments are discussed in Ref. [1].

Name	Depth (mwe)	Type	Absorber	Mass (g)
CUORICINO	3500	Thermal phonon	TeO_2	56×750
CDMS II	2100	Ionization and phonon	Ge, Si	$21 \times 250, 21 \times 100$
EDELWEISS II	4500	Ionization and phonon	Ge	21×320
CRESST II	3500	Scintillation and phonon	$CaWO_4$	33×300

of scintillation and phonons. This is done by having a main calorimeter with an absorber made out of an intrinsic scintillating material. In it, an incoming particle releases not only phonons for the main phonon signal, but also photons, which can escape the main calorimeter. With some form of light collector, these photons can be detected in a secondary calorimeter, giving the light signal. A 6 g proof of principle experiment [21] demonstrated discrimination properties at least as good as those of ionization-phonon detectors, with no complications arising from surface events. $CaWO_4$, which should have an excellent spin-independent cross section thanks to the tungsten, was used as scintillator, though other materials also showed promise (BaF_2, BGO, and $PbWO_4$ where tested; other tungstates and molybdates may function). Efforts are under way to scale the device up while maintaining a low threshold.

0.4 Prospects

Hybrid ionization-phonon calorimeters now have the best spin-independent limits. Thanks to their wider choice of targets, scintillation-phonon devices could prove an important complement to them. This is reflected in the ambitious next generation of calorimetric experiments being planned in deep underground sites (Tab. 3). Apart from CUORICINO — a scaled-up version of the Milano $\beta\beta$ experiment which will use standard calorimeters, and whose assets for dark matter will be an impressive total mass of 42 kg and the presence of tellurium (in general good for spin-independent searches and in particular with an atomic number very similar to that of iodine) — the experiments will all use hybrid calorimetric units of a few hundred grams (ionization-phonon for CDMS II and EDELWEISS II, scintillation-phonon for CRESST II) deployed in arrays of up to 10 kg. These experiments should have the sensitivity to start a thorough exploration of supersymmetric phase space (Fig. 5). Particularly in the spin-independent case, cryogenic detectors now have a window of opportunity, since the earlier techniques of ionization and scintillation which could hardly reject any background require draconian radioactivity levels in order to improve, and other promising background-insensitive techniques such as droplets or two-phase xenon are not yet fully mature [17, 22].

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